An Emerging New Direction in Remote Sensing for Earth Science: The Technology of GPS Occultations

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***Abstract*– A recently developed atmospheric remote sensing technique is undergoing rapid development. Global Positioning System (GPS) radio occultations are active limb-soundings acquired on a low-Earth orbiting GPS receiver that accurately measure the time delay of a GPS signal as it propagates through the atmosphere. Science quality GPS instruments are currently in orbit on two Earth science missions, CHAMP and SAC-C, providing data that reduces to scientifically useful profiles of atmospheric temperature, pressure, and specific humidity with sub-km vertical resolution. At the same time, these receivers are serving as technology "pathfinders" for current and future constellations of low-Earth orbiting GPS receivers.**

In this paper, we discuss recent technology developments that improve science return in the lowest 5 km of the atmosphere, an interesting region that is difficult to sound at high vertical resolution with other techniques from space. We report on receiver improvements that increase the number of occultations available from this region, data analysis improvements that improve accuracy, and the development of the first end-to-end simulator that can account for receiver performance in detail.

Throughout the discussion, we refer to other remote sensing investments deployed by NASA's Earth science enterprise, to place this new technology in a broader context. We also reference the science questions that are being addressed by GPS occultations in these strategic areas: "How well can long-term climate changes be assessed or predicted?"; "How are global precipitation, evaporation, and the cycling of water changing?"; and "How well can transient climate variations be understood and predicted?"

I. INTRODUCTION

The challenging research goals of NASA's Earth Science Enterprise demand that innovative and powerful remote sensing techniques be conceived and nurtured towards flight readiness. NASA has invested heavily in space-based technologies that measure scientifically useful properties of the atmosphere, such as global temperature profiles, concentrations of water vapor and other chemical constituents, winds, precipitation, and clouds. Given the complexity of the system being studied, it is not surprising that a wide variety of remote sensing techniques have been brought to bear, using portions of the electromagnetic spectrum from the microwave to the infrared to the visible.

The scientific information available from remote sensing depends on the physical process used to make the measurement. The *passive sounding* paradigm refers to measurement systems that receive naturally emitted radiation altered by absorption or scattering after propagating through the atmosphere. In *active sounding*, the radiation is emitted by a man-made source such as a ground or space-based microwave transmitter or laser. Examples include LIDAR systems or microwave radars for detecting clouds and winds. In space-based applications, the transmitter and receiver are often collocated, e.g. on the same spacecraft.

The Earth Science Technology Office is pursuing a relatively new form of active sounding where the radiation is emitted from a different location than the receiver. The remote sensing technique discussed in this paper is based on analyzing microwave radiation emitted by the Global Positioning System, a constellation of over 24 satellites transmitting precise timing information using onboard atomic clocks. The GPS satellites occult behind the Earth as viewed from a suitable receiver placed in low-Earth orbit (LEO), so the transmissions reach the receiver after propagating through the atmosphere's limb. The coherent nature of the transmissions leads to interesting measurement properties that complement the more traditional active and passive approaches.

Table 1. Missions carrying GPS occultation sensors

Mission	Launch	Comments
CHAMP	2000	Productive
SAC-C	2000	Productive
IOX	2001	Under evaluation for atmospheric occultations
GRACE	2002	Occultations expected in 2002
CNOFS	2005	Space weather focus – US Department of Defense
EQUARS	2005	INPE (Brazil) – proposed
COSMIC	2005	Six satellite constellation
METOP	2005	ESA
NPOESS	2009	NOAA
SBIRS Low	20XX	US Defense Department constellation of 24 satellites – proposed

The main purpose of this paper is to describe recent technical developments funded by the Earth Science Technology Office to increase the science return of GPS occultation soundings in the lower troposphere region. Because this remote sensing field is relatively new, we will

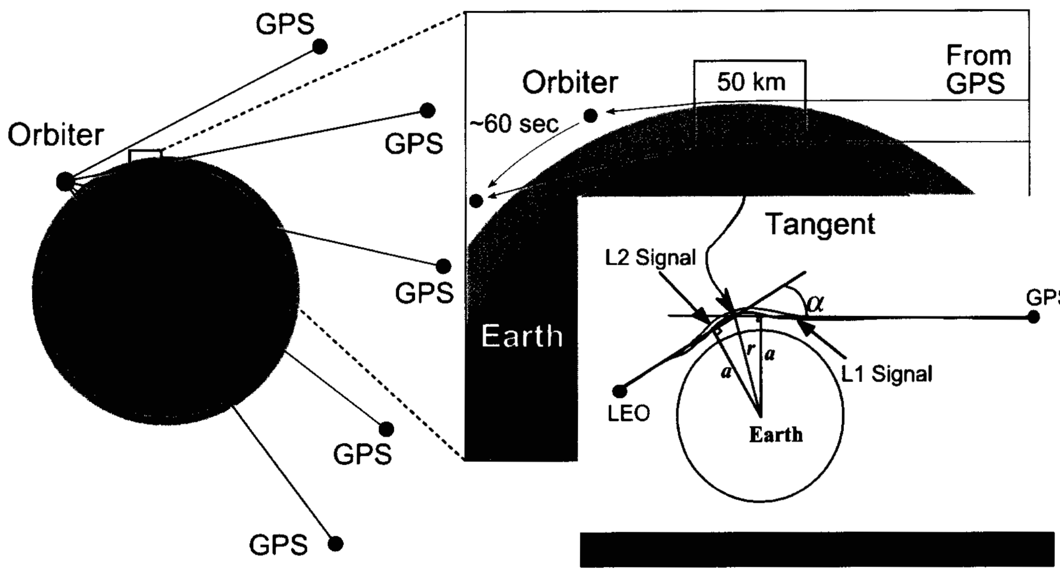

Fig. 1. The geometry of GPS occultations. Atmospherically-induced signal bending (α) can be used to infer vertical profiles of temperature and pressure. Each GPS satellite transmits a signal at two frequencies (L1 and L2) to facilitate removal of ionospheric delays.

begin by describing the GPS-based measurement, followed by a discussion of how GPS can provide useful scientific information for NASA's Earth Science Enterprise that complements more mature approaches. We will then discuss the specific technical accomplishments recently achieved at the Jet Propulsion Laboratory where an active program in GPS occultations exists using data from instruments onboard the SAC-C and CHAMP missions (and soon GRACE), which carry advanced GPS receivers specifically designed to meet Earth Science Enterprise research objectives. Finally, we conclude the paper with a look ahead at what the future holds for the GPS remote sensing paradigm. Table 1 provides a summary of missions carrying GPS atmospheric sensors.

II. GPS OCCULTATION REMOTE SENSING

Global Positioning System radio occultations are active limb soundings that measure the time delay of a GPS signal propagating through the atmosphere. This delay can be related to vertical profiles of atmospheric refractivity from which highly accurate profiles of geopotential height, temperature, pressure, and specific humidity are derived. With their global coverage, self-calibrating nature, penetration through clouds, and high vertical resolution, atmospheric radio occultations are a valuable source of data for Earth science, in the fields of weather prediction, climate monitoring and atmospheric dynamics.

The GPS currently consists of 29 satellites (nominally 24 plus a few spares), distributed in six circular orbital planes at ~55° inclination, 20,200 km altitude and with a 12 hour period. Each GPS satellite continuously transmits two L-band frequencies, L1 at ~1.6 GHz (~19 cm wavelength) and L2 at ~1.2 GHz (~24.4 cm) [1] . From the standpoint of the receiver, an occultation occurs whenever a GPS satellite rises or sets behind the Earth's limb. A schematic representation of atmospheric profiling by GPS radio occultation, using a receiver in LEO, is given in Fig. 1. The effect of the atmosphere on the occulted signal can be characterized by refraction-induced bending (α) of the signal which varies as a function of the impact parameter, a. The bending is inferred from the Doppler frequency shifts in the received signal after calibrating clock errors and geometry. The bending profile is transformed to yield atmospheric refractivity as a function of altitude, based on the Abel transform [2]. Refractivity is related to the pressure and temperature of the atmosphere according to the following formula:

$$N = a_1 \frac{P}{T} + a_2 \frac{P_W}{T^2} \tag{1}$$

where N is the refractivity, P is the total pressure, T is the temperature, P_W is the water vapor partial pressure, and a_1 and a_2 are constants (a_1 = 77.6 K/mbar; a_2 = 3.73×10^5 K^2/mbar). Once the refractivity has been determined, separate temperature and pressure profiles can be derived assuming hydrostatic equilibrium (pressure increases towards the surface due to gravity). This procedure has been used for a number of years and originated as a method for interpreting planetary occultation measurements [3,4].

In the year 2000, two satellites, the German CHAMP and the Argentinean SAC-C, were launched carrying a new generation of GPS receivers called "BlackJacks". Developed at JPL, these receivers have been collecting up to 400

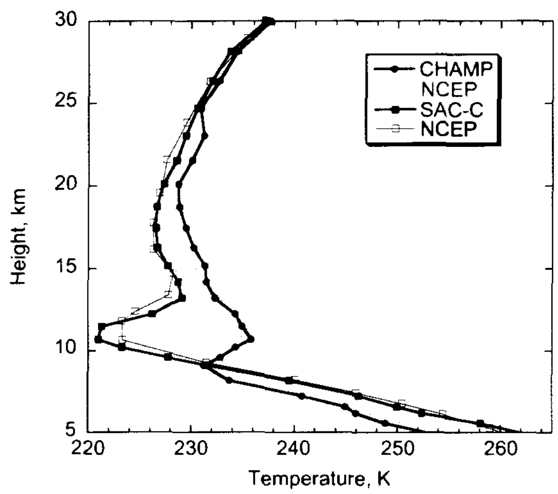

Fig. 2. Temperature profiles derived from the CHAMP and SAC-C missions, compared to model analyses which tend to smooth over sharp gradients suggested in the data.

occultations daily starting in 2001 and are providing data that complements other atmospheric sounding techniques. By the summer of 2002, with the activation of the GPS occultation receivers onboard the GRACE mission and the forward facing antenna on SAC-C, we expect to collect and distribute scientific data from approximately *1000* occultations every day.

To illustrate some of the features of radio occultations we show two nearby high-latitude occultations (at 75° North) from CHAMP and SAC-C in Fig. 2. The two occultations were chosen because of their (1) proximity, within 300 km, and (2) quite distinct features. Shown also in the figure are two profiles based on semi-daily analyses from the National Centers for Environmental Prediction (NCEP) interpolated to the locations and times of the occultations. A notable strength of occultation measurements is the ability to resolve the structure of the thermal tropopause with high vertical resolution, whereas the models are effectively smoothing this out. Such high resolution measurements can be of great significance for addressing climate change as a function of height, or the structure and dynamics of the thermal tropopause, which is crucial for understanding the dynamics of transport between the higher troposphere and the lower stratosphere.

III. Comparison of GPS Occultations with Other Techniques

Improvements in remote sensing technology generally occur in three fundamental categories: *sampling*, the regions of the Earth system being measured including how often; *information content*, the physical properties that can be extracted from the regions being examined; and *sensitivity*, the errors incurred (random and systematic) in extracting the information. Examples of information content are the concentration of trace chemical constituents such as ozone, or cloud height. Sensitivity characterizes the quantitative accuracy of the information being extracted. To place GPS occultation measurements in a broader context, we will briefly compare GPS attributes in these categories with the well-established passive sounding technique.

A. Sampling Considerations

From a scientific perspective, spatial sampling is important because the physics of the atmosphere causally connects small-scale perturbations with large scale effects. Measuring features at ever-smaller scales is likely to improve our understanding of the Earth system as a whole, and have an impact on the Earth Science Enterprise strategic science questions mentioned in the abstract. Similar comments apply to temporal sampling; the atmosphere displays significant variations over time scales from minutes to decades and longer.

The number of GPS occultations that occur for a given low-Earth orbiter is about 250 per day for a rear-facing antenna placed on the spacecraft. The GPS satellites appear to set (occult) behind the Earth's limb as viewed from the orbiter. Another 250 profiles would be available if an antenna is placed in the forward direction and the signal can be acquired as it rises up from the surface (such rising occultations have yet to be demonstrated but are theoretically possible). Neglecting less-useful occultations viewed "sideways", it is not clear how to significantly increase the number of profiles (~250 or 500) generated daily by a single GPS receiver in orbit.

In general, from a given platform, GPS occultations sample far fewer distinct regions (horizontal resolution) than nadir-viewing passive techniques that receive radiation from directly below the satellite. For example, the AIRS instrument has a nominal horizontal resolution of approximately 45 km and provides continuous coverage along the ground track. By contrast GPS occultations typically sample a region of horizontal extent 250 km, and are scattered randomly in the vicinity of the spacecraft ground track. Each occultation requires 1-2 minutes to complete.

Although occultations cannot provide the horizontal resolution of passive sounding, the relatively low-cost and multiple uses for GPS receivers in orbit is leading to ad-hoc constellations of receivers that are distributed in solar angle and inclination. This has scientific advantages over dense sampling from a single platform because a variety of geophysical conditions are probed simultaneously, reducing so-called "sampling biases", which limit information to a narrow set of local times. Local time sampling is much more comprehensive for a GPS receiver constellation than for a single satellite.

B. Information Content of GPS Occultations

The information content of GPS occultations derives from the following two physical properties of the measurement: first, scientific information is derived from the amount of signal bending (a geometrical measurement); second, the received signal is coherent (electromagnetic phase information is preserved between transmission and reception). Passive sounders work on entirely different physical principles, by analyzing the frequency spectrum of radiation emitted by thermal incoherent sources after propagating through the atmosphere. The scientific implications of these two approaches are touched on here.

The GPS signal bends in the atmosphere due primarily to vertical gradients in the refractive index of the medium (refractive index measures the degree to which the medium slows down the signal relative to vacuum). The dominant source of bending is the exponential increase of air density towards the surface. At altitudes below about 5 km where the temperature begins to rise above 250K (mid-latitudes), water in the atmosphere also contributes significantly to the refractive index gradients.

The atmospheric regions above and below a specific humidity threshold of about 0.2 g/kg define two distinct regions where the information content of the GPS occultations varies. At altitudes above the mid-troposphere where the atmosphere is dry ($P_w = 0$ in equation 1), the bending can be used to infer profiles of temperature and pressure versus height. In the lower troposphere, the water vapor contribution to refractivity requires the use of additional information to derive T and P separately. Because of the importance of measuring the global water vapor distribution, a standard approach in the wet regions is to use occultations to derive water vapor content instead of temperature; temperature from a weather analysis is needed as additional input [5]. This technique works very well in the tropics where temperatures are typically known to better than 2 K.

In the dry region above the mid-troposphere, the scientifically useful properties of the occultation measurement are the high vertical resolution and the direct retrieval of temperature and pressure as a function of height. High vertical resolution (ranging from 100 meters near the surface to 1.5 km at altitudes of 25 km) is useful for detecting the characteristics of gravity waves in the upper atmosphere [6,7] and the detailed temperature structure of the tropopause region which often exhibits layering (e.g. Fig. 2) [8]. The direct retrieval of integrated pressure versus height (geopotential height) to an accuracy of about 7-8 meters may be useful for detecting subtle climate signals [9,10].

An important feature of GPS occultations is that they are sensitive to fine-scale refractivity structure. Typical causes are water vapor (humidity or clouds), and sharp changes in temperature near the tropopause and boundary layer regions (see the CHAMP measurement near the tropopause in Fig. 2). This sensitivity is possible because the radiation maintains full coherence, and is a remarkable property for a space-borne remote sensing application.

It is useful to compare the information content from GPS with the passive sounders. Passive approaches cannot achieve the highest vertical resolutions obtainable from occultations. For example, the most advanced infra-red sounder NASA has yet developed, AIRS, has a *target* resolution of 1 km. Microwave limb sounders typically achieve 2-3 km vertical resolution. Also, passive nadir-viewing sounders such as AIRS retrieve vertical temperature profiles referenced to pressure, not height. As mentioned previously, this may have implications for detecting subtle climate signatures.

In the wet troposphere, the sounders can separately retrieve water vapor concentrations among other atmospheric constituents (although infrared sounders cannot penetrate beneath clouds). GPS occultations do not directly provide unique chemical information, although in the tropics water vapor concentration can be derived relatively accurately because temperatures remain close to climatological values [5]. What GPS can achieve uniquely is sensitivity to small scale structure and sharp refractivity gradients caused by water vapor clumpiness, clouds, thermodynamic forcing near the tropopause, or atmospheric viscosity (e.g. the boundary layer). Because the GPS signal travels as a coherent wavefront, small refractivity variations occurring over vertical distances of about 0.1-0.5 km (Fresnel zone scale in the lower troposphere) cause destructive interference and readily detectable fluctuations in signal amplitude and phase.

The incoherent nature of the radiation source for passive sounders does not generate interference patterns, so is less sensitive to temperature or water vapor structure sizes below the vertical resolution limit (1 km for AIRS). It is likely that GPS will strongly complement passive approaches in understanding atmospheric processes near the tropopause, and in scientific investigations where it is important to understand global features of the boundary layer. Fully exploiting GPS sensitivity to fine scale structure is an area of active research.

C. Sensitivity of GPS Occultations

All measurements exhibit noise, both random and systematic in nature. It is particularly important to understand and control systematic drifts in temperature measurements when climate signals are being studied. The broad error characteristics of GPS occultation measurements have been reported widely (see [11] for example) and within a height range of 5-30 km, accuracies of 1 K can be achieved. This is similar to the target precision for AIRS and is considered a useful error level for scientific work [12]. We note that this temperature represents an average over the horizontal sampling region of the occultation (~250 km length).

Below the mid-troposphere, such accurate temperature retrievals cannot be achieved routinely because of the water vapor contribution to refractivity. In this case, the GPS refractivity data have been used to estimate the water vapor content of the sampled region assuming *a priori* temperature profiles (e.g. from a weather model analysis). This works particularly well in the tropics where temperatures vary little from climatological values. In data assimilation applications to improve weather forecasting, resolving the ambiguity is avoided by inputting refractivity or bending angle directly into the model [13].

The algorithm for converting raw GPS frequency information into profiles of refractivity is rigorously valid only for an atmosphere that is symmetric about the occultation tangent point. Significant variations (for example, weather fronts) within the sampling region may cause errors when interpolating temperature to the tangent point of the occultation. This error does not appear to be a major concern [14] although further research is warranted.

A more significant source of error in occultation retrievals is the diffraction effect mentioned earlier. The amplitude and phase of the received signal fluctuates rapidly due to sharp atmospheric structures within a Fresnel zone size (0.1-0.5 km in the lower troposphere). Retrieval techniques must be developed that account for diffraction or temperature errors of 5 K or more are possible (an example is shown later). Diffraction correction represents one of the technology research areas for the GPS remote sensing technique, and is described in the next section. An important scientific application is capturing refractivity structures in the lower troposphere that generally elude other space-borne remote sensing methods.

Passive sounder measurements have been subject to controversy when reporting temperature accuracies at the level of 1 K or below [15]. Achieving this accuracy requires careful calibration of the instrument spectral response (detected power as a function of wavelength), requires an understanding the properties of the emitted radiation (for example, if contaminated by clouds) and the frequent use of external data sets for calibration support. The retrieval algorithms, which are nonlinear iterative codes, require *a priori* assumptions that can introduce biases under certain circumstances.

The challenge of tying passive sounder measurements to an absolute temperature scale stable over decades is widely recognized [16]. Since GPS relies on timing information and not irradiance measurements, the temperature calibration process is subject to completely different errors than the passive sounder case. This can provide very useful independent validation data. Atmospheric occultation measurements are self-calibrating in the sense that the calibration procedure requires only GPS data, not a separate instrument or source that is externally calibrated. No reference is necessary to an external timing standard. In contrast, passive sounders must run calibration procedures periodically and the calibration source must be tied to an external standard. When studying long-term temperature trends with GPS, it may be desirable (based on current technology) to concentrate on the smoother atmospheric regions that do not cause significant diffraction effects.

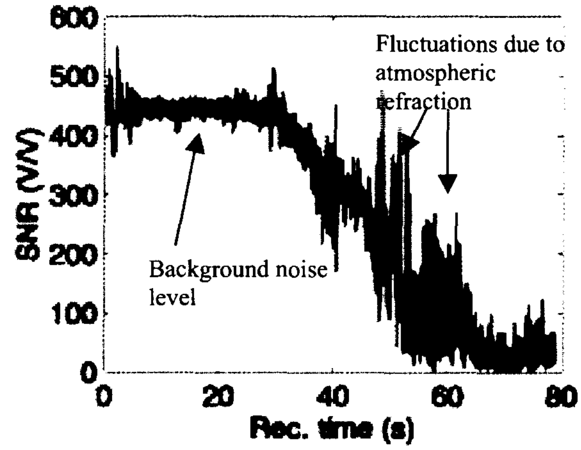

Fig. 3. Plot of signal amplitude versus time for a CHAMP occultation. The lower troposphere region is reached at about 50 seconds. The amplitude dip at 70 seconds may due to a sharp refractivity gradient when the signal reaches the boundary layer.

IV. RECENT TECHNOLOGY DEVELOPMENTS FOR GPS OCCULTATIONS

GPS occultation remote sensing was first demonstrated with the GPS/MET mission launched in 1995, a joint project of NSF, NASA, NOAA, and JPL. Although very successful as a proof-of-concept, the receiver technology at that time could only be used effectively during brief periods when the GPS signal encryption was turned off. In 2000, the CHAMP and SAC-C missions were launched carrying the more advanced BlackJack receiver design, capable of acquiring high-quality data despite signal encryption. The GPS Earth Observatory science data analysis project at JPL routinely processes raw data from these missions and has accumulated a database of science products from over 30,000 occultations, distributed to the scientific community via the GENESIS web site (http://genesis.jpl.nasa.gov). Occultation data from the GRACE mission will be included in the summer of 2002.

Our technology objective is to develop new algorithms for the flight receivers and the ground processing system that improve science return from GPS occultations by: (1) increasing the number of profiles acquired in the lower troposphere; and (2) increasing the quality of the science products particularly in the lower troposphere. Fortunately, new technology can be implemented and tested *in flight* because the BlackJack receivers perform many functions in software. When new algorithms are developed, they are uploaded to the receiver for testing and can become

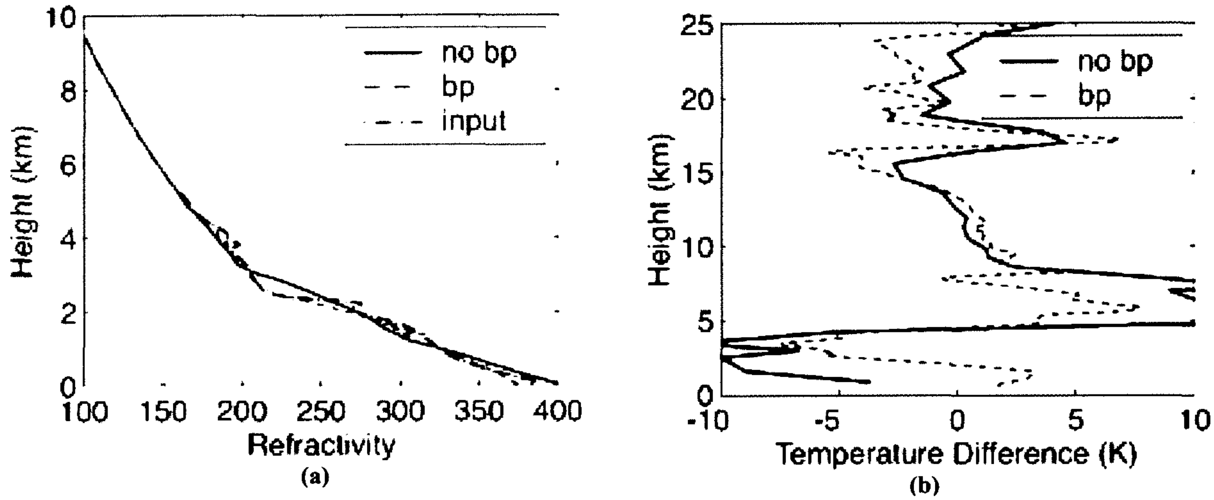

Fig. 4. The left panel (a) shows refractivity errors that can occur if signal diffraction is not corrected by back-propagation. The retrieval with back-propagation (green) more accurately recovers the input refractivity (red) than the standard technique. The right panel (b) shows the temperature residual for two CHAMP occultation retrievals, with and without back-propagation. The same model profile has been subtracted from each retrieval.

permanent changes to the receiver processing if the testing is successful.

A.. Flight Instrument Algorithm to Increase Acquired Profiles

It was evident from the GPS/MET experiment that the receiver stopped acquiring a significant number of occultations within 2-5 km of the surface. Below about 5 km altitude, atmospheric defocusing, exacerbated by inhomogeneities in the atmosphere, cause the electromagnetic wave to spread and self-interfere reducing signal amplitude, and causing rapid phase and amplitude fluctuations. Standard phase-lock-loop algorithms used at that time were not suited to these conditions. An example of the highly dynamic signal that results is shown in Fig. 3, where signal amplitude is plotted versus time during the occultation (the ray path reaches the lower troposphere after about 50 seconds).

Conventional GPS receiver technology typically cannot maintain lock when the signal amplitude fluctuates downward below a threshold (see the depressed region in Fig. 3 at 70 seconds). If the low signal persists for a few seconds, signal reacquisition is attempted and the occultation effectively ends. We have implemented an innovative solution to this problem and tuned a new algorithm that is robust to temporary reduction in signal strength. The receiver automatically changes tracking mode when the received signal power becomes too low for conventional tracking.

The signal amplitude often fades due to strong refractivity layering. The fading triggers a new tracking mode that extrapolates the receiver's model of phase and phase rate based on the most recent measurements when signal strength is adequate. These episodes of fading can last for several seconds while the signal frequency is changing rapidly, on the order of 10 Hz/s. In order to maintain an estimate of the proper loop frequency when/if the signal returns, an exponentially filtered estimate of the frequency rate is continuously updated and maintained while the signal is strong. This rate estimate adjusts the model frequency during periods of signal weakness to improve chances of frequency/phase lock once the signal strength returns. During this "fly-wheeling" period, phase feedback to the tracking loop is disabled but the full phase estimate (model plus residual) is still output as usual, so the mode switch is transparent to the ground processing system.

The benefits of this fly-wheeling approach are evident in the data collection statistics acquired with the CHAMP mission. For example, significantly more occultations now reach as far down as the final half-kilometer of the atmosphere: 62% currently versus 32% previously. Clearly, further improvements are possible.

B. Using Signal Coherence to Improve Retrievals

We have recently developed significant technical advances for our data analysis system to improve recovery of scientific observables in the lower troposphere. A central challenge in this region is correct interpretation of the received phase information when interference effects are present. Using standard retrieval techniques which are based on geometrical optics, the recovered temperature profiles generally lose accuracy. Although the ultimate solution to this problem is

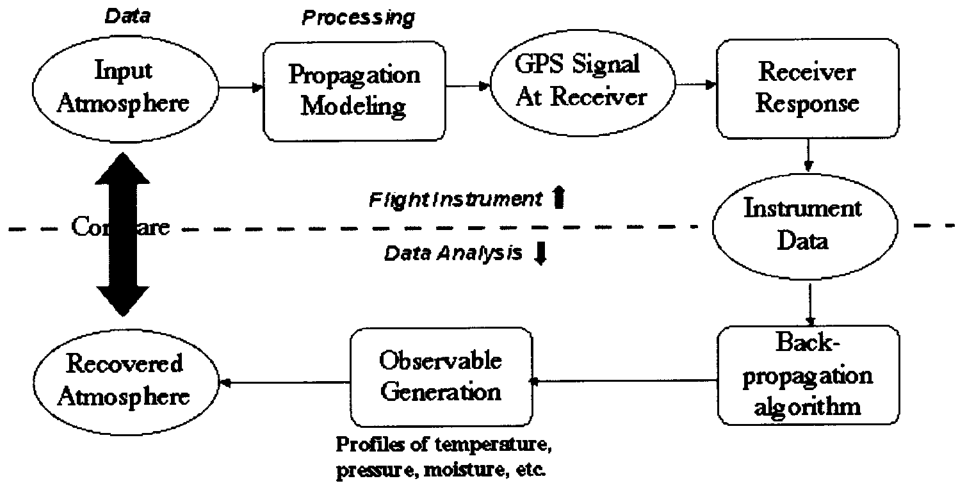

Fig. 5. A block diagram of the end-to-end occultation simulator.

not yet available, an intermediate approach takes advantage of the coherent nature of the received radiation and use diffraction theory to reconstruct the signal at a location closer to the occultation tangent point where interference effects are generally reduced. The physical basis for this reconstruction is that the free space propagation of a coherent electromagnetic wavefront is completely determined if the amplitude and phase are known over any surface encompassing the source. In the case of occultations, this principle does not strictly apply because the amplitude and phase are measured along the receiver trajectory, a line rather than a surface. However, assuming no variation in the transverse direction, the two-dimensional Kirchoff diffraction integral can be used to perform the back-propagation [17, 18]. By contrast, the radiation source for passive sounding is incoherent, and there is no analog to the diffraction integral. This significantly reduces the sensitivity of passive sounders to small-scale atmospheric density structures and it is not possible to achieve "super-resolution" in a similar fashion.

The effectiveness of back-propagation is illustrated in Fig. 4a. A realistic refractivity profile from an in-situ radiosonde measurement was used as input to our occultation simulation system (described later). The input profile (red line) shows an interesting refractivity kink at 3 km altitude probably associated with the atmospheric boundary layer. Also plotted is a back-propagated retrieval (green), and a retrieval without back-propagation (blue). Near the refractivity kink, fractional refractivity errors of ~10% are observed if back-propagation is not used (possibly leading to temperature errors of up to 25 K). With back-propagation, the retrieved refractivity is nearly indistinguishable from the input.

Fig. 4b shows the difference in two temperature retrievals using actual CHAMP data. Although no ground truth is available in this case, it is clear that back-propagation alters the retrieval temperature by more than 5 K, a scientifically significant amount. We expect that in this case the back-propagated retrieval improves accuracy.

C. End-to-End Simulation System

We have implemented an end-to-end simulation of the GPS remote sensing technique that significantly improves the efficiency of assessing current and future technical advances. Using this simulator, we can assess proposed improvements to the flight instrument algorithms before they are uploaded to the spacecraft, tune the algorithms to optimize performance for expected atmospheric conditions, and characterize expected errors in the scientific observables under a wide variety of realistic atmospheric conditions. As far as we are aware, this is the only simulator of the GPS occultation measurement that can realistically account for the effect of receiver tracking error on the retrieval.

The simulator is schematically depicted in Fig. 5 showing processing steps and the resulting data sets produced at each step. Starting with a synthetic vertical refractivity profile possibly obtained from an *in situ* observation, we model the propagation of the GPS signal through the atmosphere. This produces a realistic phase and amplitude signature at a location of our choosing that may represent the receiver location. The signal data are fed into a software version of the receiver which contains the same algorithms (based on the same software) as the actual flight hardware; the output of this module represents the receiver *estimate* of the signal phase and amplitude. At this stage, the simulated data emulate what is downloaded from the receiver to the ground processing system. We then use the data analysis system as if it were acting on real data: first the back-propagation step is performed and then observable extraction (soundings of temperature, pressure, etc.). The retrieved atmospheric quantities can be compared to the synthetic input profile for detailed evaluation.

As part of the development of this simulator, we implemented a high-fidelity simulation of GPS signal propagation using a sophisticated multiple-element approach. Signal changes due to a synthetic atmosphere are applied at a discrete number of planes, known as "phase screens", and the signal phase is modified by a prescribed amount at each plane. Carefully constructed, we can model and study the impact of vertical and horizontal atmosphere variations. This will allow further exploration of the utility of signal coherence for probing fine scale refractivity structures in the troposphere.

V. Future Technology Directions for GPS Occultations

GPS occultations is a relatively new remote sensing technology that shows great promise. In this paper, we have identified those aspects of the technique that make it unique and should be further developed for the Earth Science Research enterprise. Despite recent mission successes, international research efforts, and several future missions planned, the technology is still in its infancy. For example, rising occultations have yet to be demonstrated, and further improvements are possible to increase tracking robustness in the lower troposphere, using so-called "open loop" techniques which are more robust implementations of the recently developed fly-wheeling algorithm.

For long term climate monitoring, the important development centers around accuracy and precision in temperature and pressure retrievals. In the dry upper troposphere/stratosphere region, it appears that the error sources are fairly well understood. It is important to find new ways of validating the retrievals and understanding the scientific implications of the sampling region.

At these higher altitudes, recent research indicates that interesting data on turbulence in the mesosphere is available from GPS (Dong Wu, private communication). There is also interest in pushing the retrievals to higher altitudes, to study planetary-scale waves.

The lower atmosphere is currently a strong research focus because it is an extremely important region for understanding atmospheric processes and global warming, and GPS occultations provides unique information due to it's sensitivity to small-scale refractivity structures. Clearly, increasing the information content of the occultations when water vapor is present remains an important focus of further research.

The technology of GPS occultations is moving away from the approximation of geometrical optics. Taking diffraction into account not only allows for better accuracy, but also opens the possibility that new types of atmospheric structures can be sensed remotely. This area is poised for a breakthrough with significant scientific implications.

The challenge is enormous: obtaining an understanding of a physical system as complex and chaotic as the Earth's atmosphere using measurements from orbiting platforms. Observations will play the central role in pushing this understanding to new levels, and techniques such as GPS occultations, that contribute unique information over global scales and over long periods, will undoubtedly lead to new knowledge and insight into the workings of planet Earth. Indeed, as the research literature demonstrates, advances in our understanding are already occurring.

Acknowledgment

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